Geiger-mode avalanche photodiodes as photodetectors in Cherenkov astronomy

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Outline

$N_{p.e.} = PDE \times N_{photons}$

- G-APDs for a telescope camera: the FACT project

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- G-APDs for a telescope camera: the FACT project
- G-APD characterization: some key properties
  - Angle dependence
  - Analytical description of saturation and crosstalk
  - Precision of the reconstructed number of photons

Principle of Imaging Air Cherenkov Telescopes

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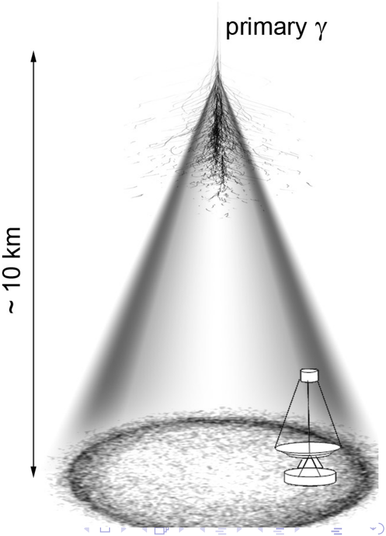
- Primary γ produces air shower



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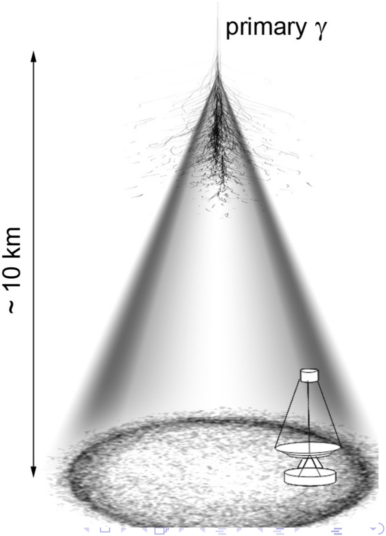
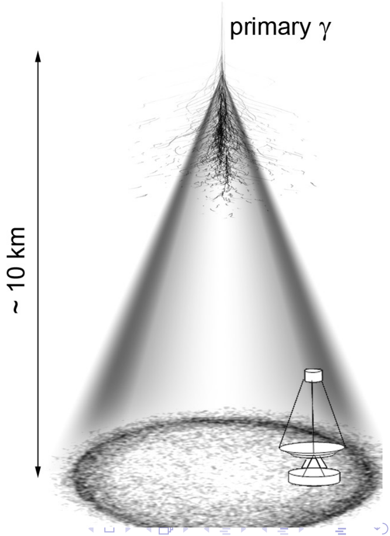
- Secondary particles emit Cherenkov light



Principle of Imaging Air Cherenkov Telescopes

- Primary γ produces air shower
- Secondary particles emit Cherenkov light
- Telescope within the light cone detects the Cherenkov light



Camera requirements

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$\Rightarrow$ Photomultiplier match the requirements, but there is room for improvements...

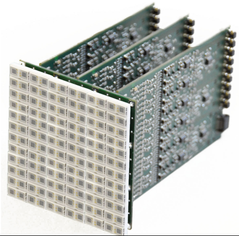
G-APDs as a PMT replacement?

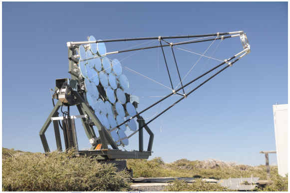
Some considerations:

- Higher PDE (especially when folded with Cherenkov spectrum)
- Afterpulses timing characteristic favorable (exponential distribution instead of fixed delay $\rightarrow$ less false triggers)
- Afterpulses spectrum favorable (identical to the dark count spectrum)
- Aging, ruggedness (survival of rough handling and light exposure)
- But: small sensitive area (Winston cones?), difficult handling of crosstalk...

The FACT Project

- The First G-APD Camera Test Project wants to evaluate the possibility of a G-APD based camera for a Cherenkov telescope (DWARF: Dedicated multiWavelength AGN Research Facility).
- A prototype module (M0) is now being assembled for first studies (144 G-APDs, each 4 G-APDs summed to form one pixel).
- First Air shower detection expected within the next days.

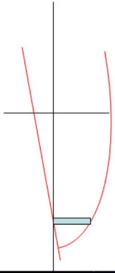




Angle dependence: Winston cones

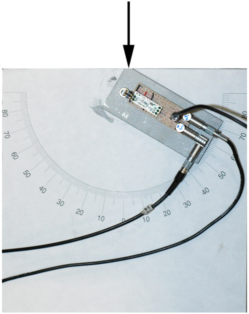
- Light concentrators (Winston cones) are used to eliminate dead space around the sensitive area.
- Simulations: higher concentration factors (A_{in}/A_{out}) can be achieved using solid instead of hollow cones.
- Due to the Liouville theorem: larger angles at the detector surface for solid cones.

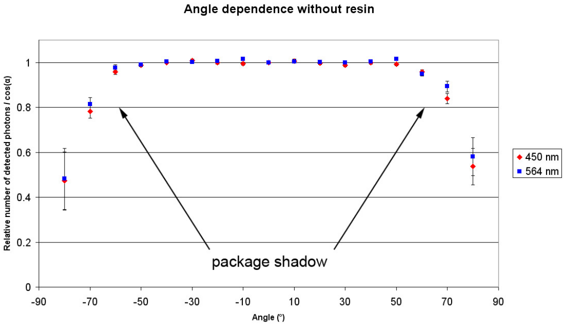
What is the angle dependence of the photon detection efficiency for G-APDs?



Angle dependence: measurement

The epoxy resin was removed to get rid of refraction.





⇒ No angle dependence was found within the measurement error (approx. 1%) up to 60°.

Calculation

A certain signal size $\tilde{N}$ is measured. What is the corresponding number of photons impinging on the diode N_{inc}?
Relevant effects:

- Photon detection efficiency
- Statistical saturation, described by a function $S(n, m)$.
- Crosstalk
- Afterpulses
- Dark counts (can be neglected if pedestals are taken...)

S(n,m) is either $S = m(1 - (1 - \frac{1}{m})^n)$ [[1]] or $S = m(1 - e^{-\frac{n}{m}})$ (simplified). The arrival time spread of the photons is assumed to be small compared to the recovery time.

[1] Stoykov et al., JINST 2 P06005, (2007)

Calculation

- Number of initial breakdowns N_0:
  $N_{inc} \overset{PDE}{\rightarrow} N_{p.e.} = PDE \times N_{inc} \overset{saturation}{\rightarrow} N_0 = S(N_{p.e.}, N_{cells})$
- Number of cells triggered by crosstalk N_{CT}:
  $u_{ct} N_0 \overset{saturation}{\rightarrow} N_{ct} = S(\frac{N_c - N_0}{N_c} u_{ct} N_0, N_c - N_0)$
- Number of afterpulses N_{AP}:
  $\mu_{ap}(N_0 + N_{ct})$
- Measured number: $\tilde{N} = N_0 + N_{CT} + N_{AP}$

PDE: Photon detection efficiency

μ_{ap}: Average number of afterpulses per breakdown in units of full breakdowns (incl. cell recovery), depends on the integration gate length ($\mu_{ap} = 0$ for pulse height measurements).

u_{ct}: Average number of cells triggered by crosstalk for an empty sensor, as opposed to

p_{ct}: Crosstalk probability, probability to trigger one or more cells through crosstalk

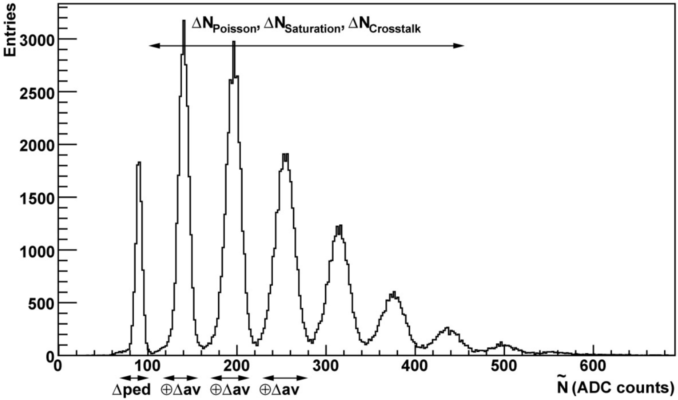
Precision of reconstructed number of p.e.

If we calculate $N_{p.e.}$ backwards according to the previous slide, what is the precision of the obtained number? How do different characteristics contribute?

$$N_{p.e.} \pm \underbrace{\Delta N_{p.e.}}_{Poisson} \quad \rightarrow \quad \tilde{N} \pm \Delta \tilde{N} \quad \rightarrow \quad N_{p.e.,rec} \pm \Delta N_{p.e.,rec}$$

Precision of reconstructed number of p.e.

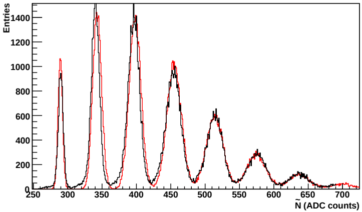
The calculation for $\tilde{N}$ only gives mean values, the measurement values are distributed:

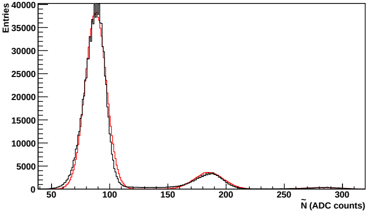


Statistical simulation

Input parameter: cell number, crosstalk probability, pedestal width Δped, avalanche variations Δav, (mean) photon number, Poisson statistics

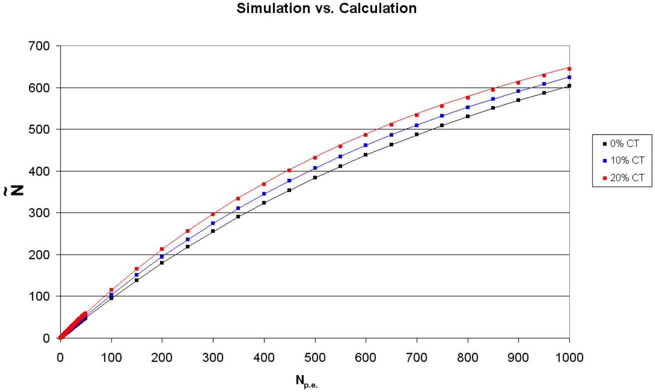
$\Rightarrow$ good agreement with measured spectra





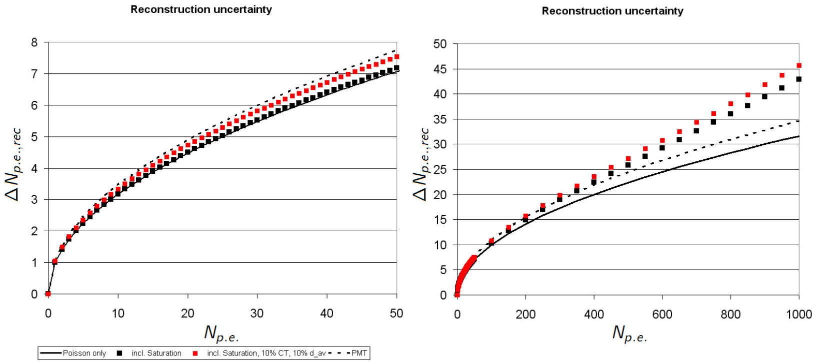
Comparison of the calculation and the simulation

The simulation and the calculation are in good agreement.
Example (900 cells):



Dots: simulation, lines: calculation

Precision of reconstructed number of p.e.

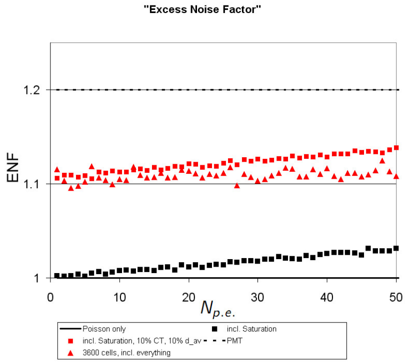


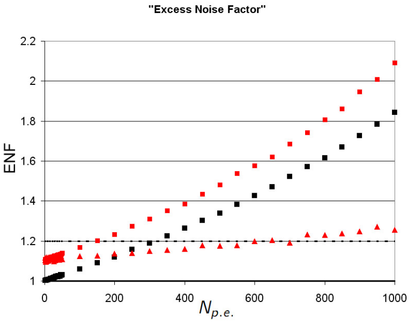
- Poisson error dominates the reconstruction uncertainty (up to $N_{p.e.} \approx N_{cells}$).
- $\Rightarrow$ Eliminate Poisson contribution using the definition of the excess noise factor.

Excess noise factor

Definition of the excess noise factor (ENF):

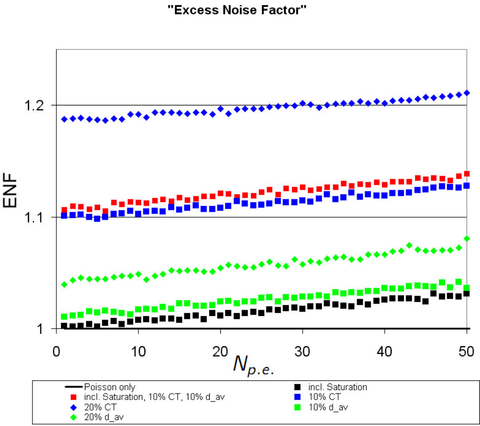
$$\frac{\Delta N_{p.e.,rec}}{N_{p.e.,rec}} = \sqrt{\frac{ENF}{N_{p.e.,rec}}} = \sqrt{\frac{ENF}{N_{p.e.}}}$$





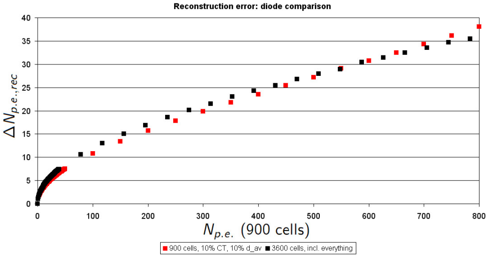
Excess noise factor

- Why "ENF" in quotes?
  The idea of the ENF is to have a measure for the reconstruction precision independent of the number of incoming photons. This principle is lost for G-APDs due to saturation if the original definition is used.
- What are the contributions to the ENF when saturation is not important (i.e. $N_{p.e.} << N_{cells}$)?
  - Crosstalk: $F \approx 1 + p_{ct}$
  - Avalanche variations: $F \approx 1 + \Delta_{av}^2$



Which diode is best suited for our application?

Higher PDE vs. more cells?



- ⇒ Reconstruction error is very similar, thus the decision can be made based on other criteria.
- For us: there is a lot of night sky background (40 MHz - 2 GHz per diode). It is thus favorable to have a small gain, and more cells means also less influence of the NSB on the non-linearity ⇒ smaller cells, but more of them.

Conclusion and Outlook

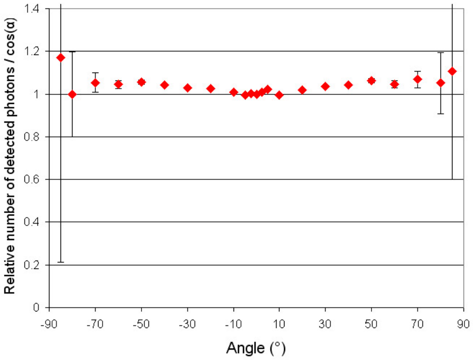
- The angle dependence of the photon detection efficiency was measured for two wavelengths. No dependence was found.
- A statistical simulation was used to determine the influence of saturation, crosstalk and avalanche variations on the reconstruction resolution.
- Besides the Poisson statistics of the number of incoming photons, the main contributions are crosstalk ($N_{p.e.} << N_{cells}$) and saturation ($N_{p.e.} \approx N_{cells}$).

Outlook:

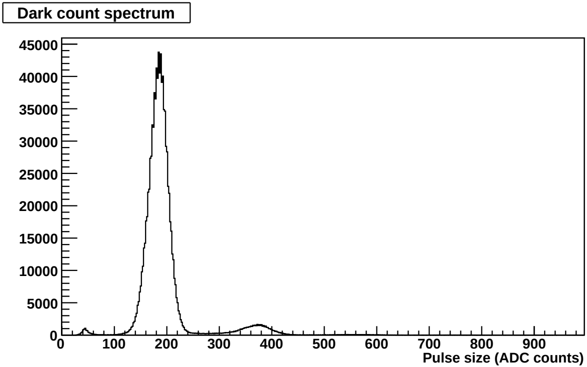
- Experimental verification of the simulation
- (Analytical description for the reconstruction resolution)
- Building of the G-APD camera, evaluating its behaviour under "outdoor" conditions.

Backup slides

Angle dependence with resin



Accidental triggers: dark count spectrum



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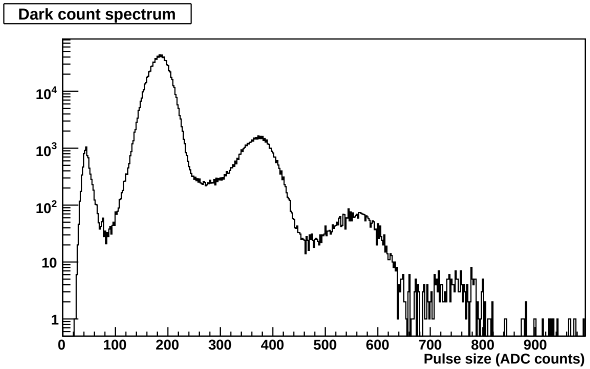

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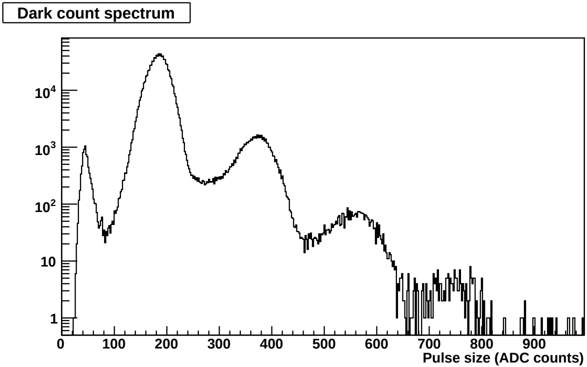

- Crosstalk defines the dark count spectrum.

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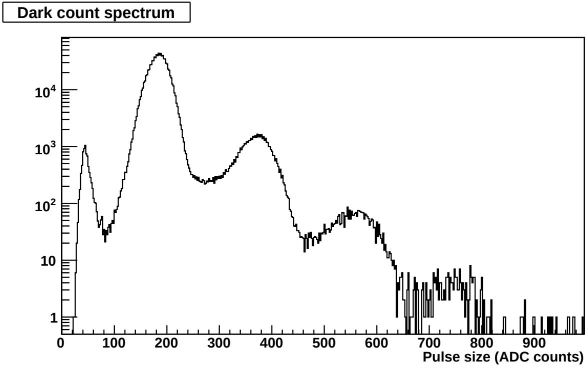

- Crosstalk defines the dark count spectrum.
- Spectrum of the night sky background is identical.

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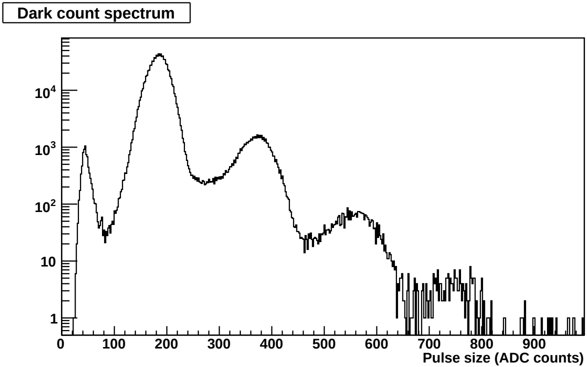
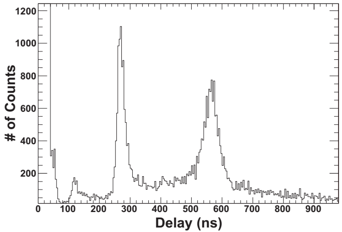
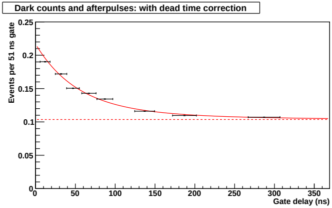


- Crosstalk defines the dark count spectrum.
- Spectrum of the night sky background is identical.
- Spectrum of the afterpulses is identical.

Accidental triggers: afterpulses





- PMT: afterpulses at distinct times after initial pulse
- G-APDs: afterpulses with exponentially decreasing probability after initial pulse (two components with 50 ns and 140 ns).

Afterpulses have the same spectrum as the NSB and do not occur at distinct times. ⇒ They can be treated as an increased dark count/NSB rate.